SUMMARY This paper discusses a dual-stage detection scheme composed of coarse detection stage and refined detection stage for the continuous detection operation of Ultra-Wideband (UWB) detect and avoid (DAA). The threshold factor for the probability of indefinite detection is first proposed and defined to combine the two stages. The proposed scheme focuses on the integration of two different detection schemes with different complexities in order to reduce total computational complexity. A Single-carrier Frequency Division Multiple Access (SC-FDMA) uplink system operating in a Time Division Duplex (TDD) mode is utilized to evaluate the proposed detection scheme. Simulation results indicate that the proposed scheme can make a tradeoff between the detection performance and the computational complexity by setting the probability of indefinite detection.

**key words:** dual-stage detection, coarse detection, refined detection, threshold factor, probability of indefinite detection

1. Introduction

Detect and avoid (DAA) is essential for Ultra-Wideband (UWB) system to coexist with International Mobile Telecommunications-Advanced (IMT-Advanced) system, which will be implemented and occupy 3.4–3.6 GHz band in the near future [1]–[3]. The 3rd Generation Partnership Project (3GPP) LTE-Advanced system can fully reach or even surpass the requirements on IMT-Advanced system within the ITU-R time plan [4], [5]. Therefore, the LTE-Advanced system is supposed to be the victim system for UWB system and the coexistence issues between these two systems should be investigated.

The coexistence issues between WiMAX system and UWB system have been discussed in [6]. The detection of the transmitted signal of the victim system is prerequisite for DAA. Both the downlink and the uplink of the victim system can be tested by UWB system. However, detecting the uplink is relatively easier than detecting the downlink since the UWB device is closer to the User Equipment (UE) than to the Base Station (BS) [6]. Comparing with WiMAX signal detection, the minimum bandwidth of LTE-Advanced signal is narrower and more sophisticated detection scheme is required. The Single-carrier Frequency Division Multiple Access (SC-FDMA) system has been selected as the uplink of LTE-Advanced system. In 3.4–3.6 GHz band, only the Time Division Duplex (TDD) mode is recommended in the specification of LTE-Advanced [7]. There are two main types of subcarrier mapping ways in frequency domain, distributed mapping (or interleaved mapping) and localized mapping [8], [9]. In order to achieve high throughput and low system complexity, the localized mapping scheme is only supported in 3GPP [10]. The distribution feature of the localized mapping way in frequency domain can be utilized by UWB systems in DAA for the detection for SC-FDMA signal.

The energy detection (ED) scheme has been investigated in DAA [2]. ED is simple and efficient, however, it suffers from noise uncertainty and cannot distinguish a signal type [11]. Cyclostationarity feature detection (CFD) can differentiate the signal type in low signal-to-noise ratio (SNR) [11] and reach better detection performance. However, the large computational complexity is its limitation. Therefore, a dual-stage detection scheme combined with ED and CFD is proposed, which hopefully utilizes the spectrum features of the victim signal and conquers the limitations of ED and CFD. Moreover, a tradeoff between the detection performance and the computational complexity may be achieved.

Coarse detection (CD) and refined detection (RD) are two detection stages of the proposed dual-stage detection scheme. CD is the first detection stage and RD works as the second detection stage. CD initially senses the victim signal of the target frequency band. When CD cannot provide a definite detection result, the same signal samples saved in the detector will be check again by RD and the final detection result will be determined. The advantages and limitations of ED and CFD make them be the natural candidates for CD and RD, respectively. To further reduce the complexity of the whole system and make full use of the characteristics of the victim signal, the low-complexity cyclostationarity feature detection approach (abbreviated to Low-complexity Spectrum Correlation Density, LSCD) [12] is supposed to be utilized.

The two-stage (or two-step) detection schemes have been discussed in [13], [14] and a bi-thresholds method has been proposed in [15]. [13] presents the performance analysis based on detection time and [14] introduces an autoregressive (AR) model in the analysis of two-step sensing scheme. [15] uses a sensing approach with a double-threshold to decrease the transmission burden of sensing information. Different from the above schemes, this paper focuses on the combination of two detection stages with two different detection schemes by using the threshold factor and the probability of indefinite detection ($P_{\text{ID}}$). The first stage of the detection selects resource blocks (RBs) that may be
in use and the second stage checks the existence of the LTE-Advanced signal with cyclostationarity detection. A tradeoff between the detection performance and the computational complexity can be achieved by setting $P_{TD}$.

The remainder of the paper is organized as follows. Section 2 firstly presents a coexistence model of UWB systems and LTE-Advanced systems, followed by a simple introduction of the DAA mechanism. The SC-FDMA uplink system is also introduced. The dual-stage detection scheme with CD and RD is presented in Sect. 3. The definitions of the threshold factor and the probability of indefinite detection are also given in the same section. Section 5 shows the simulation results and the paper is concluded in Sect. 6.

2. Coexistence Model and the SC-FDMA Uplink System

2.1 Coexistence Model of UWB System and LTE-Advanced System

Figure 1 presents the coexistence model of UWB systems and LTE-Advanced systems, which is similar to the DAA Zone Model [2] and a coexistence model between WiMax systems and UWB systems [6]. In this model, the LTE-Advanced system is the victim system to the UWB system. The transmission included downlink and uplink should be detected and protected by UWB system with the DAA mechanism. In 3.4–3.6 GHz band, LTE-Advanced system is the victim system to the UWB system is also introduced. The dual-stage detection scheme operating in the TDD mode is considered in this paper.

In DAA, there are two types of detection operations, initial detection and continuous detection [2], [16]. The initial detection is used to sense the victim signal of the target frequency band initially, and the continuous detection is utilized to monitor regularly the target band. In the continuous detection operation, the signal level of the victim system is sensed continuously [2]. The proposed dual-stage detection scheme can be utilized in the continuous detection operation in order to reduce the computational complexity and improve the detection performance.

2.2 SC-FDMA Uplink System

SC-FDMA uplink system has been described in [8] and [10]. Figure 2 presents the structures of the UE transmitter and the Base Station (BS) receiver. The $M$ input symbols $s[m](m = 0, ..., M - 1)$ are transformed into frequency domain $S[l]$}

$$S[l] = \sum_{m=0}^{M-1} s[m] \cdot \exp \left(-j\frac{2\pi ml}{M}\right), \quad l = 0, ..., M - 1. \quad (1)$$

Each of DFT outputs $S = [S[0], ..., S[M - 1]]^T$ is then mapped to one of the $N$ orthogonal subcarriers. The localized mapping way is supported by 3GPP [10], [17]. The localized mapping way can be defined as

$$X[k] = \begin{cases} S[l], & k = D + N_{Sub} \cdot \Delta (\lfloor l/N_{Sub} \rfloor) \\ + l \text{ mod } N_{Sub} & 0, \quad k = \text{others}, \end{cases}$$

where $D$ is band margin and $N_{Sub}$ is the number of the subcarriers per RB. $\lfloor \alpha \rfloor$ indicates the largest integer that does not exceed $\alpha$. $\Delta (\lfloor l/N_{Sub} \rfloor)$ is a random integer, which belongs to $[0, N_{RB} - 1]$ and $N_{RB}$ is the total number of RBs.

A RB distribution example of localized SC-FDMA signal is shown in Fig. 3. The example is based on a practical SC-FDMA uplink system with 10 MHz bandwidth (BW) [10], [18]. In this figure, the number of subcarriers $N$, the number of RBs $N_{RB}$ and the number of subcarriers in one RB $N_{Sub}$ are set to be 1024, 50 and 12, respectively. The margin $D$ is $(N - N_{RB} \cdot N_{Sub})/2 = 212$. In time domain, the transmission time unit is the time slot, which is 0.5 ms. 7 SC-FDMA symbols make up one time slot. Note that the same slot structure is taken in the FDD mode and the TDD mode [10]. It means that the distribution ways of RBs in the FDD mode and the TDD mode are the same in a specific slot.

![Fig. 1 Coexistence model.](image1)

![Fig. 2 SC-FDMA uplink system.](image2)
The output signal \( x[n] \) expressed in time domain is generated by \( N \)-point inverse DFT (IDFT),

\[
x[n] = \frac{1}{N} \sum_{k=0}^{N-1} X[k] \cdot \exp \left( \frac{2\pi j nk}{N} \right), \quad n = 0, 1, \ldots, N - 1.
\]  

The receiver does the inverse action of the transmitter to receive the transmitted SC-FDMA signal tainted from a non-ideal channel.

The proposed detector shown in Fig. 4 takes a similar structure with the SC-FDMA receiver excepting De-Mapping and M-IDFT components. This is different from the detector in [6], which is built in a UWB receiver and reuses the DFT component. WiMAX utilizes OFDMA mode, in which a specific user may occupy one or more sub-channels containing 24 subcarriers (262.56 kHz) [19]. It is difficult for such a detector to detect WiMAX signal well when it occupies only single sub-channel. This is the reason why [6] indicates that the dedicated DFT hardware with more frequency bins is required to detect low bandwidth WiMAX signal.

SC-FDMA signal utilizes 180 kHz RB shown in Fig. 3, which contains 12 subcarriers with 15 kHz per subcarrier. Compared with the WiMAX signal, it is more difficult for the detector in [6] to detect SC-FDMA signal especially when high detection performance is required. Please notice that such a detector can also reuse some components of the UWB receiver.

Both ED and CFD can be implemented with this detector structure. Note that ED is built in time domain and located after A/D component without the DFT block while CFD is in frequency domain.

3. Proposed Dual-Stage Detection Scheme with Threshold Factor and Probability of Indefinite Detection

3.1 Dual-Stage Detection Scheme for SC-FDMA Uplink Signal

In detection operation, ED working as CD tests the victim signal. When CD cannot provide a definite result, RD is required to check the existence of the cyclostationarity feature from the same victim signal samples. RD takes the LSCD scheme and presents the last detection result.

Both ED and LSCD follow a binary hypothesis test. The test can be described as,

\[
\mathcal{H}_0 : y[n] = w[n],
\]

\[
\mathcal{H}_1 : y[n] = \sum_{p=0}^{P-1} h[p] x[p-n] + w[n],
\]  

where \( y[n], x[n] \) and \( w[n] \) are the \( n \)-th samples of the received signal, the transmitted SC-FDMA signal and the additive white Gaussian noise (AWGN), respectively. The channel type (AWGN or Multipath) is indicated by the factor \( h \) and the number of multipaths \( P \). For the AWGN channel, the parameter \( P \) is set to be 1 and only \( h[0] \) is calculated. For a multipath fading channel, \( h[p] \) is a complex random variable denoting the channel fading on the \( p \)-th path. Two Rayleigh fading models (JTC Indoor Office A and JTC Indoor Office B) are included in simulations [20]. Suppose that \( x[n], w[n] \) and \( h[p] \) are independent of one another. \( \mathcal{H}_1 \) indicates the SC-FDMA uplink signal is present and the target frequency band is occupied while \( \mathcal{H}_0 \) denotes that the target frequency band is empty.

3.2 Coarse Detection Stage with Energy Detection Scheme

An energy detector for \( N \) transmitted signal \( y[n] \) in time domain is defined as

\[
D_E = \sum_{n=0}^{N-1} |y[n]|^2.
\]  

According to the hypotheses test, the test statistic of \( D_E \) follows a central \( \chi^2 \)-distribution with \( N \) degrees of freedom under the hypothesis of \( \mathcal{H}_0 \). When \( \mathcal{H}_1 \) is valid, it follows a non-central \( \chi^2 \)-distribution with the same degrees of freedom. Based on the central limit theorem (CLT), the test statistic of \( D_E \) approximately follows a Gaussian distribution when the sample number \( N \) is large enough [21], [22]. The test statistic can be approximately described as

\[
\mathcal{H}_0 : D_E \sim CN(2N\sigma_w^2, 2N\sigma_v^2)
\]

\[
\mathcal{H}_1 : D_E \sim CN(2N(\sigma_w^2 + \sigma_v^2), 2N(\sigma_w^2 + \sigma_v^2)^2),
\]  

where \( \sigma_w^2 \) and \( \sigma_v^2 \) are the variances of the AWGN and the victim signal, respectively. \( \sigma_v^2 \) is also defined as

\[
\sigma_v^2 = E[[x[n]]^2],
\]
is defined as \( \gamma \) and detection of ED \( \gamma \) under two hypotheses. For a threshold \( \gamma \), the probability of detection of ED is determined as

\[
P_{\text{DE}} = Q\left(\frac{\gamma - N(\eta^2 \sigma_e^2 + \sigma_w^2)}{\sqrt{2N(\eta^2 \sigma_e^2 + \sigma_w^2)^2}}\right),
\]

where \( Q \) denotes the complementary cumulative distribution function. The probability of false alarm \( P_{FA} \) is defined as

\[
P_{FA} = Q\left(\frac{\gamma - N \sigma_e^2}{\sqrt{2N \sigma_w^2}}\right).
\]

In order to integrate the two detection stages, the threshold factor \( \rho \) and the probability of indefinite detection \( P_{ID} \) are proposed. Figure 6 denotes their definitions. \( \rho \) is defined to be a small bidirectional shift, which can be calibrated with the ratio of the given specific threshold \( \gamma \). Compared with Fig. 5, \( \rho \) changes the single threshold to an interval \( \gamma \rightarrow [\gamma - \rho, \gamma + \rho] \). \( \gamma + \rho \) is the high threshold \( \gamma_{CH} \) and \( \gamma - \rho \) is the low threshold \( \gamma_{CL} \).

When the detector of CD is greater than the high threshold \( D_C \geq \gamma_{CH} \), it means that SC-FDMA uplink signal from the target frequency fragment is detected. If \( D_C < \gamma_{CH} \), it means that the target fragment is available. Otherwise, when \( \gamma_{CH} > D_C \geq \gamma_{CL} \), it means that CD cannot present a definite result and RD will be required.

The probability of indefinite detection is defined as

\[
P_{ID} = Q\left(\frac{\gamma - \rho - N(\eta^2 \sigma_e^2 + \sigma_w^2)}{\sqrt{2N(\eta^2 \sigma_e^2 + \sigma_w^2)^2}}\right)
\]

\[= Q\left(\frac{Q^{-1}(P_{FA}) - \rho/(\varepsilon \sqrt{2N}) - \varepsilon \sqrt{N}/2}{\varepsilon + 1}\right),
\]

\[
P_{ID} \text{ indicates the probability that CD locates in the threshold interval } [\gamma_{CL}, \gamma_{CH}], \text{ on the other hand, it also indicates the probability that the target frequency band needs to be checked by RD.}
\]

Substituting Eq. (9) into Eq. (10) gives the expression of \( P_{ID} \),

\[
P_{ID} = Q\left(\frac{Q^{-1}(P_{FA}) + \rho/(\varepsilon \sqrt{2N}) - \varepsilon \sqrt{N}/2}{\varepsilon + 1}\right).
\]

where \( Q^{-1} \) denotes the inverse complementary cumulative distribution function. In Eq. (11), \( \varepsilon \) is defined as the signal-to-noise ratio (SNR),

\[
\varepsilon = \frac{\eta^2 \sigma_e^2}{\sigma_w^2}.
\]

For the constant false alarm probability (CFAR) test, \( P_{ID} \) is mainly determined by \( \rho \) under the conditions of the fixed number of samples \( N \) and the specific SNR environment. Under such assumption, \( P_{ID} \) and \( \rho \) can determine mutually. For a practical detection system, \( P_{ID} \) (or \( \rho \)) can be determined ahead according to the signal level or the signal type of the victim signal. Those information can be available in the continuous operation stage of DAA [2].

The probability of the coarse detection can be calculated by

\[
P_{DC} = Q\left(\frac{\gamma + \rho - N(\eta^2 \sigma_e^2 + \sigma_w^2)}{\sqrt{2N(\eta^2 \sigma_e^2 + \sigma_w^2)^2}}\right)
\]

\[
= Q\left(\frac{Q^{-1}(P_{FA}) - \rho/(\varepsilon \sqrt{2N}) - \varepsilon \sqrt{N}/2}{\varepsilon + 1}\right).
\]

Note that, \( P_{FA} \) is still for the whole detection process. \( P_{DC} \) is
obviously less than $P_{DE}$ for the shift of the threshold. However, the refined detector will check the ‘suspicious’ subband and compensate the reduction.

3.3 Refined Detection Stage with Low-Complexity Cyclostationarity Feature Detection Scheme

The low-complexity cyclostationarity feature detection method (LSCD) proposed in [12] works as RD. The cyclostationarity feature detector is denoted by the accumulative sum of spectral correlation density (SCD) function [12], [23]. The detector for the received SC-FDMA uplink signal in frequency domain can be described as

$$D = \sum_{k=0}^{N-1} \sum_{\lambda=-(N-1)}^{N-1} Y[k] Y^*[k + \lambda],$$

where $k$ and $\lambda$ are the discrete frequency index and the discrete cyclic frequency index, and $N$ is the total number of subcarriers. $Y[k]$ and $Y^*[k + \lambda]$ are the received SC-FDMA signal in frequency domain, and the symbol * denotes complex conjugate. The unit of $k$ and $\lambda$ is the subcarrier spacing in frequency domain. For a specific SC-FDMA signal example shown in Fig. 3, the number of subcarriers $N$ is 1024.

The LSCD can be defined as

$$D_{RB}^{LSCD} = \sum_{k=0}^{N_{Sub}-1} \sum_{\lambda=-(N_{Sub}-1)}^{N_{Sub}-1} Y[k + \lambda + N_{Sub} \cdot r] \cdot Y^*[k + \lambda + N_{Sub} \cdot r] \cdot \Psi_s[k, \lambda],$$

where $\Psi_s[k, \lambda]$ is a block window function for the $r$-th RB. The block window function $\Psi_s[k, \lambda]$ is determined by the spectrum feature of the victim signal and can be defined as

$$\Psi_s[k, \lambda] = \begin{cases} 1, & (E[X[k + \lambda + N_{Sub} \cdot r]] > 0) \\ 0, & (\text{others}) \end{cases}$$

The index of RB is $r$, $r = 0, \ldots, N_{RB} - 1$. Here for all RBs, the following block window function is employed

$$\Psi[k, \lambda] = \begin{cases} 1, & (k \in [0, \ldots, 11], (k + \lambda) \in [0, \ldots, 11]) \\ 0, & (\text{others}). \end{cases}$$

In a detection slot, the detector checks each of all $N_{RB}$ RBs and the maximum of them will be the last result. Therefore, the result of RD is

$$D_R = \max_{0 \leq r \leq N_{Sub}} |D_{RB}^{LSCD}|,$$

where the symbol $\max$ means that the amplitude of the detection and $D_{RB}^{LSCD}$ indicates the detection result generated from the $r$-th RB.

The detection rule for RD is straightforward,

$$H_1 \quad \frac{D_R \geq \gamma_R}{H_0},$$

where $\gamma_R$ denotes the detection threshold of RD.

The detection result of the whole detection scheme is defined as

$$P_D = P_{DC} + P_{DR},$$

where $P_{DR}$ is the probability of detection of RD. The proposed dual-stage detection scheme can fulfill the varied detection requirements by setting different threshold factor $\rho$.

The computational complexity analysis of the proposed detection scheme and the coming computer simulations both consider a practical 10 MHz SC-FDMA uplink system, with parameters given in Table 1 [10], [18], [24]. LSCD, DD and ED are the abbreviations of the low-complexity cyclostationarity detection, the proposed dual-stage detection and the energy detection, respectively.

Table 2 shows the computational complexities of the proposed scheme, comparing with those of ED and LSCD. The complexity is measured by the number of multiplication operations of RD ($N_{RD}$) and LSCD ($N_{LSCD}$) are in frequency domain shown in Eq. (14). The computational complexities of such two operations can be regarded

<table>
<thead>
<tr>
<th>Table 1 System parameters.</th>
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<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>Carrier frequency</td>
</tr>
<tr>
<td>Bandwidth</td>
</tr>
<tr>
<td>Sampling frequency</td>
</tr>
<tr>
<td>DFT size ($N_{DFT}$)</td>
</tr>
<tr>
<td>Number of RB ($N_{RB}$)</td>
</tr>
<tr>
<td>Subcarrier spacing</td>
</tr>
<tr>
<td>Number of subcarrier per RB ($N_{Sub}$)</td>
</tr>
<tr>
<td>Number of symbol per Slot ($N_{Symb}$)</td>
</tr>
<tr>
<td>Slot duration</td>
</tr>
<tr>
<td>Detection duration for LSCD and ED ($N_{Slot}$)</td>
</tr>
<tr>
<td>Detection duration for CD and RD ($N_{Slot}$)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2 Complexity analysis.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probability of false alarm $P_{FA}$</td>
</tr>
<tr>
<td>Signal-to-noise ratio SNR</td>
</tr>
<tr>
<td>Number of multiplication for CD $N_{CD}$</td>
</tr>
<tr>
<td>Number of correlation for RD $N_{RD}$</td>
</tr>
<tr>
<td>Number of multiplication for ED $N_{ED}$</td>
</tr>
<tr>
<td>Number of correlation for LSCD $N_{LSCD}$</td>
</tr>
<tr>
<td>Complexity of proposed scheme $N_{ID} = N_{DC} + P_{ID} + N_{RD}$</td>
</tr>
</tbody>
</table>

where $P_{ID}$ denotes the probability of indefinite detection.
ZHANG and SANADA: DUAL-STAGE DETECTION SCHEME FOR ULTRA-WIDEBAND DETECT AND AVOID

Fig. 7 Complexity versus the ratio of the threshold factor to the threshold \( \rho/\gamma \), with \( P_{FA}=0.01 \) and \( SNR=-5dB, \) 0dB and 5dB.

Fig. 8 Relation between the probability of indefinite detection \( P_{ID} \) and the ratio of threshold factor to threshold \( \rho/\gamma \), for \( P_{FA}=0.01 \) and \( SNR=-5dB, \) 0dB and 5dB.

as the same for each multiplication operation. The complexity of the proposed dual-stage scheme \( (N_{DD}) \) is calculated from \( N_{CD}, N_{RD} \) and the probability of indefinite detection \( P_{ID} \). The complexity of the proposed scheme is inherently determined by the threshold factor \( \rho \).

Figure 7 presents the complexities of the proposed dual-stage scheme, ED and LSCD. The complexity of the proposed scheme is lower than that of LSCD. The maximum complexity of DD with \( SNR=-5 dB \) almost is 70% of that of LSCD. The complexity of DD decreases when \( SNR \) is large. It indicates that the complexity of the proposed scheme can be reduced when the detection environment is good.

Figure 8 presents the relation between the threshold factor \( \rho \) and the probability of indefinite detection \( P_{ID} \) and the probability of indefinite detection \( P_{ID} \) can determine each other.

Figure 9 shows the empirical PDF distributions of \( D_E \) under two hypotheses \( H_0 \) and \( H_1 \), respectively, comparing with the theoretical Gaussian distributions using the same means and variances. SC-FDMA signal with parameters shown in Table 1 is included in this simulation. \( SNR \) is 10dB and 2 time slots with \( 2 \times N_{DFT} = 2048 \) samples in the time domain are utilized. The channel mode is AWGN and the number of occupied RB is set to be 1 (12 subcarriers). This figure verifies that energy detection approximately follows Gaussian distribution very well.

4. Simulation Results

In computer simulation, the 10 MHz SC-FDMA uplink system with parameters shown in Table 1 is also included. Extra parameters (e.g., channel models) for simulations are given in Table 3.

To evaluate the proposed scheme with fair comparisons, the detection periods of LSCD and ED are set to be 2 time slots and those of CD and RD are set to be 1 time slot. The multipath Rayleigh channel models are Indoor Office A and Indoor Office B [20]. Table 3 gives also main parameters of the JTC Indoor Office A model and the JTC Indoor Office B model. The probability of indefinite detection \( P_{ID} \) is utilized to indicate the threshold factor \( \rho \). On the other hand, \( P_{ID} \) also indicates the probability that the second detection stage is required.

Figures 10 and 11 denote the detection performances of LSCD, DD and ED under two multipath indoor circumstances. \( P_{ID} \) is set to be 0.2, 0.5 and 0.8, respectively. The probability of false alarm \( (P_{FA}) \) is 0.01. The detection performance of the proposed scheme achieves gradually that of LSCD with increasing \( P_{ID} \). These two figures indicate that the detection performance of the proposed detection scheme can become controllable by setting varied \( P_{ID} \). The detection performances in Fig. 10 are better than those in Fig. 11, which indicates the effect of different channel models.

The receiver operating characteristic (ROC) performances under two multipath indoor circumstances are pre-
Table 3 Simulation parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of active UE</td>
<td>1</td>
</tr>
<tr>
<td>Number of occupied RBs</td>
<td>3</td>
</tr>
<tr>
<td>SNR</td>
<td>0–20 dB</td>
</tr>
<tr>
<td>Number of simulation trials</td>
<td>5000</td>
</tr>
</tbody>
</table>

Channel Model 1

- Rayleigh Multipath: Indoor Office A
- RMS Delay Spread: 35 ns
- Number of Tap: 3

Channel Model 2

- Rayleigh Multipath: Indoor Office B
- RMS Delay Spread: 100 ns
- Number of Tap: 6

Fig. 10 Probability of Detection ($P_D$) vs. SNR(dB) (Indoor Office A channel, for $P_{FA} = 0.01$ and $P_{ID} = 0.2, 0.5, and 0.8$. No. of occupied RBs is 3).

Fig. 11 Probability of Detection ($P_D$) vs. SNR(dB) (Indoor Office B channel, for $P_{FA} = 0.01$ and $P_{ID} = 0.2, 0.5, and 0.8$. No. of occupied RBs is 3).

Fig. 12 ROC performance ($P_D$ vs. $P_{FA}$) in Indoor Office A channel and $P_{ID} = 0.2, 0.5, and 0.8$. The number of occupied RBs is 3 and SNR = 0 dB.

Fig. 13 ROC performance ($P_D$ vs. $P_{FA}$) in Indoor Office B channel and $P_{ID} = 0.2, 0.5, and 0.8$. The number of occupied RBs is 3 and SNR = 0 dB.

Fig. 14 ROC performance ($P_D$ vs. $P_{FA}$) for low $P_{FA}$ in Indoor Office A channel and $P_{ID} = 0.2, 0.5, and 0.8$. The number of occupied RBs is 3 and SNR = 3 dB.

The detection performance is also affected by the data rate of SC-FDMA uplink signal, which is denoted by the number of the occupied Resource Blocks (RBs). Note that the number of occupied RBs in both of the detection stages in the proposed scheme is the same due to the refined detection will check the same signal samples when the coarse de-
tection cannot provide a definite detection result. The maximum number of occupied RBs in a 10 MHz SC-FDMA uplink system is 50. Figure 15 shows the effects of different number of occupied RBs on the detection performance. The numbers of occupied RBs are set to be 1, 3, 10, 25, and 50 of total 50 RBs. This figure indicates that the detection performance of the proposed scheme can increase fast when the number of occupied RBs changes from 1 to 10.

5. Conclusions

The energy detection method and low-complexity cyclostationarity feature detection method are selected to be coarse detection and refined detection, respectively. 10 MHz SC-FDMA uplink signal is utilized to evaluate the proposed scheme. The dual-stage detection scheme with the threshold factor and the probability of indefinite detection has been discussed in this article. The tradeoff between the detection performance and the computational complexity can be achieved by setting the parameter of the probability of indefinite detection.

Acknowledgement

This work is supported in part by a Grant-in-Aid for the Global Center of Excellence for high-Level Global Cooperation for Leading-Edge Platform on Access Spaces from the Ministry of Education, Culture, Sport, Science, and Technology in Japan.

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